Design, simulation, and realization of solid state memory element using the weakly coupled GMR effect

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Design, Simulation, and Realization of Solid State Memory Element Using the Weakly Coupled GMR Effect

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***Abstract*—We found that in a weakly coupled giant magnetoresistive (GMR) sandwich the small-field response's slope is dependent on its past magnetic history. Based on this storage mechanism, we designed a binary solid state memory element. Simulation results show that it operates on the general principle of storing a binary digit in the hard component and sensing nondestructively its remanent state by switching the soft component in such a way that the magnetic state of the hard component is unaltered, thereby causing a dramatic GMR polar readout. So far a 1-b experimental apparatus has been realized.**

I. Introduction

RECENTLY, terms such as multimedia, super information highways, video on demand, and interactive communications have become popular in the information communication community. As one example of storage devices, magnetoresistive random access memory (MRAM) using a magnetoresistive (MR) or giant magnetoresistive (GMR) effect as a read-out mechanism has attracted greater and greater interest from fundamental as well as technological viewpoints due to its nonvolatility, compactibility, and fast transient response properties [1]–[5]. This paper presents the design, simulation and realization of a solid state memory using the weakly coupled GMR effect. We conclude that weakly coupled GMR elements [6]–[9] with two ferromagnetic components can improve MRAMs significantly because of their low switching fields (<10 Oe) and intermediate magnetoresistance ratio (4% ~ 13%, in general higher than the ~2% of permalloy). Among the basic requirements for MRAMs, low switching fields lead to lowered threshold excitation currents and hence narrowing of word lines as the result of thermal considerations. Also, high output signal causes an obvious reduction in read access time, as illustrated in Fig. 1. The fact that the magnetization of NiFe can be switched at a frequency of 1 GHz [10] and the reality of high-quality lithography at 0.05 μm and less [11] make it possible to expect a advanced magnetic storage whose density will be 10^{10} b/cm^2 in the 21st century. If this is realized, MRAMs may compete with any solid state integrated memory, and potentially with magnetic disks in some application [1]. The position of GMR memory in various storage devices is given in Fig. 2.

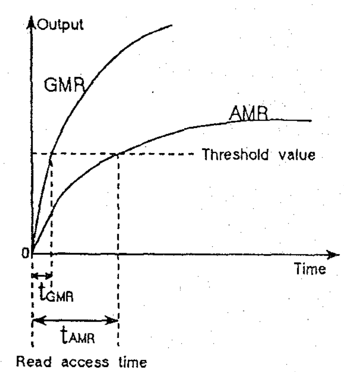

Fig. 1. Comparison of read access times.

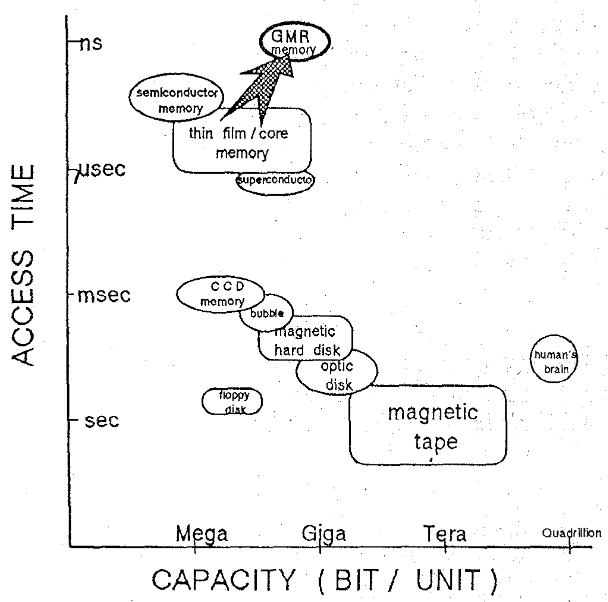

Fig. 2. Comparison of various storage devices.

II. Design

We designed a memory cell configuration using a weakly coupled GMR sandwich as shown in Fig. 3. This

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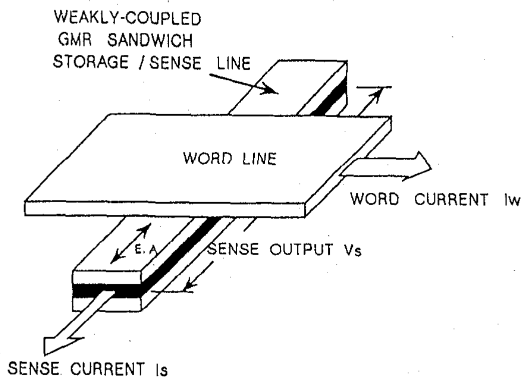


Fig. 3. Schematic structure of memory cell.

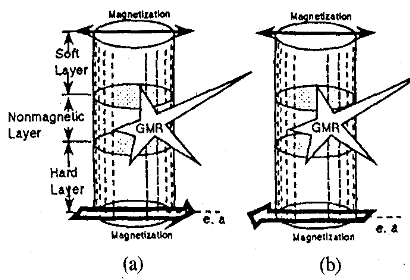


Fig. 4. Schematic mechanism of solid state memory using weakly coupled GMR effect. (a) State of 0. (b) State of 1.

mode requires only a GMR storage/sense line, with longitudinal easy axis, and a word line, orthogonal to the storage/sense line.

In principle, in structures exhibiting the GMR effect the resistance is lower when alternate magnetizations are parallel than when they are antiparallel. In a weakly coupled GMR sandwich there are two kinds of ferromagnetic components which possess different coercivities spaced with a nonmagnetic conductive film. A high GMR signal can be produced if the soft component can be reversed without reversing the hard component [6]. We considered that the hard component is used for the data storage and the soft component is used for data readout. Concretely, the magnetization in the hard component tends to point in one of two antiparallel easy directions, and these directions can be used to represent a stored 1 or a 0. In this paper the appointment is made that the remanent magnetization turning left represents 1 whereas one turning right represents 0. On the other hand, switching the magnetization of the soft component leads to a dramatic GMR signal as readout. The schematic diagram for binary memory using weakly coupled GMR effect is shown in Fig. 4.

Appropriate selection of fields leads to a method of writing a particular bit in a two-dimensional (2D) array where neither the easy direction field (with selected value) nor the hard direction field (with selected value) by themselves are able to switch the material, but the two in combination will. The hard direction field is provided by the sense current, assumed to flow almost along the intermediate layer (for example, Cu) because of its large conductivity, and the easy direction field is with the word line current. The above memory mode, which uses 2D selection for writing, also provides a possibility of 2D nondestructive readout (NDRO). NDRO can be achieved by applying a field below the hard component's threshold with the word line. When a plus pulse word current *Iw* passes through the word line, a plus or minus (corresponding to a binary data) pulse sense output *Vs* should appears across that GMR storage/sense line. The expected writing and reading timing diagram is shown in Fig. 5.

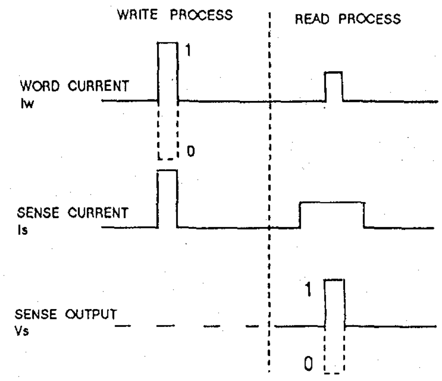


Fig. 5. Expected writing and reading timing diagram.

III. Simulation

We established an engineering model [12], [13] to demonstrate the detailed mechanism in the above design. The model is based on the coherent rotation and uniaxial anisotropy assumptions. Generally, MRAMs need a submicron cell size and pitch. For these very small dimensions, it is difficult to contain a magnetic domain wall. Hence the consideration that the switching characteristics of the films behaves like a single domain is reasonable.

As shown in Fig. 6, assume two ferromagnetic components of identical thickness having the uniaxial anisotropy (Ku_1 and Ku_2) with easy axes parallel to each other. Assume also the angles of the magnetizations with the easy axis are θ_1 and θ_2 and the angle of the applied field is ψ. In this calculation we assume $\psi = 45°$. The inclination of the applied field is for the consideration of 2D selection of memory cell in application. The parameters are taken as experimentally measured. The anisotropy fields of the soft component and the hard component are assumed to be 8 Oe and 28 Oe, respectively; the exchange coupling between the two components is assumed to be ferromagnetic (parallel) coupling, and its value is 2 Oe. Please note that the coupling's value is so weak that it is even less than the soft component's coercivity (whose theoretical value is 4 Oe). For this reason, this type of GMR is named a weakly coupled one. The angles of the magnetizations in two layers are chosen such that they minimize the energy function which covers the anisotropy and external field terms in the two components, respectively, and the ferromagnetic exchange term between the

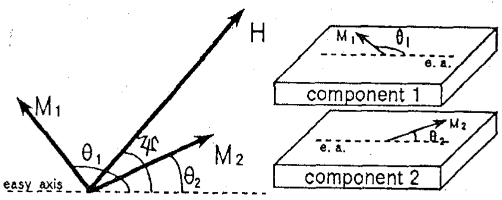


Fig. 6. Calculational diagram.

two components. The total energy per unit volume may then be expressed as

$$E = \left(\tfrac{1}{2}\right)(E_1 + E_2) + A_{12}\cos(\theta_1 - \theta_2) \tag{1}$$

where $Ei = Kui \sin^2 \theta i - MiH \cos(\psi - \theta i)$, $i = 1$ for the soft component and $i = 2$ for the hard component. A_{12} is the exchange constant, and Mi is the saturation magnetization ($M_1 = 1000\ \mu/\text{cm}^3$ and $M_2 = 500\ \mu/\text{cm}^3$).

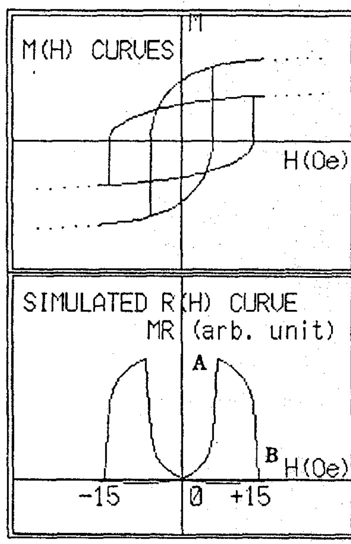
The resistance is calculated by the square of sine of the angle between the magnetizations in the two layers. It can be given by

$$\text{GMR}(H) = G * \sin^2 \frac{\theta_1(H) - \theta_2(H)}{2}. \tag{2}$$

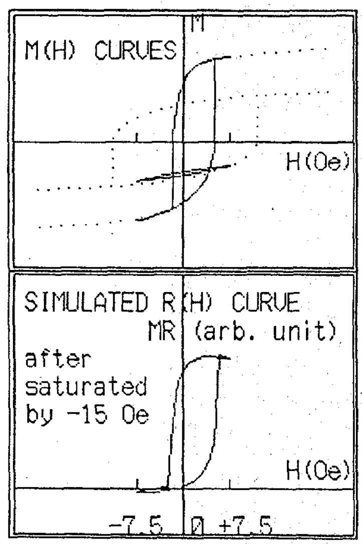
where G is the coefficient of the GMR effect.

We calculated the resistance versus applied field $R(H)$ transfer curves under an excitating field with various strength. The switching of the double ferromagnetic layers with different coercivities gives rise to the double-hump shaped main loop depicted in Fig. 7(a), where the applied field is between ± 15 Oe. From this main loop the two switching thresholds at point A and point B correspond with the magnetization reversals of the soft and the hard component, respectively. The magnetization in the soft component rotates in weak field below point A while that of the hard is not saturated up to point B. Consider a process with increasing field. The sharp increase in resistance starts when the magnetization of the soft component begins to rotate (below A). The maximum of resistance is observed at A where the direction of the soft component's magnetization has just reversed. With further increasing of the field (exceeding A), the direction of the hard component's magnetization also turns to the field direction and subsequently the resistance gradually decreases (and vice versa).

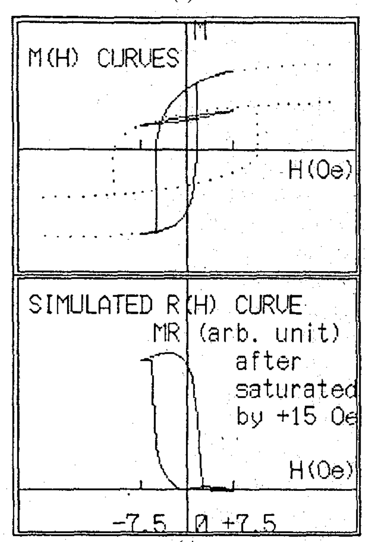
Figure 7(b) and (c) illustrates the $R(H)$ response's minor loops operating in the mode in which only the soft component is switched by applying a field between ± 7.5 Oe. In Fig. 7(b) the element is initially polarized to the negative direction by a field of -15 Oe, while in Fig. 7(c) it is initially polarized to the plus direction by $+15$ Oe. In these minor loops of small-field GMR response one can expect a shift since the initially polarized hard component blocks the spins of the soft component through the ferromagnetic exchange interaction. From Fig. 7(b) and (c) we found a storage mechanism: The slope of the small-field response $R(H)$ (minor loop) depends on its past magnetization history. That is to say, after being magnetically



(a)

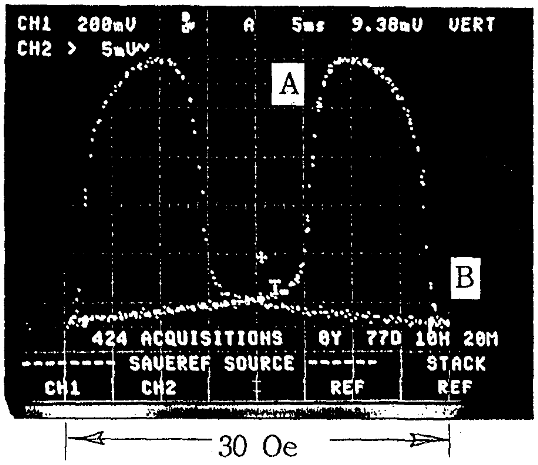


(b)

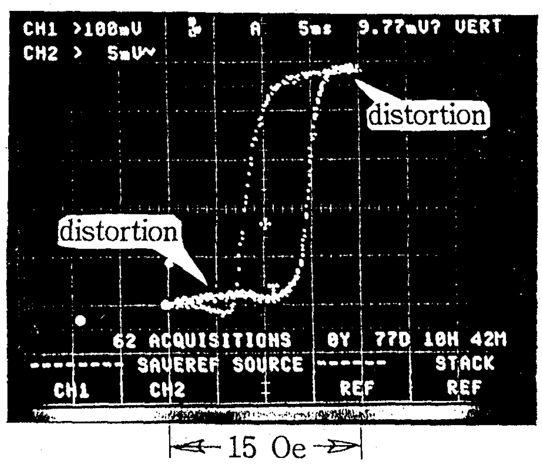


(c)

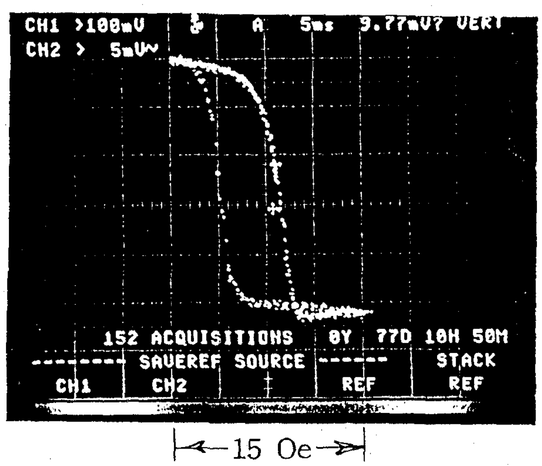
Fig. 7. Simulation results. (a) Main loop. (b) Minor loop. (c) Minor loop.



(a)



(b)



(c)

Fig. 8. Experimental results. (a) Main loop in which the readout is between ± 15 Oe. (b) Minor loop in which the applied field is between ± 7.5 Oe but the sample is initially saturated by the field of -15 Oe. (c) Minor loop in which the applied field is between ± 7.5 Oe but the sample is initially saturated by the field of $+15$ Oe.

polarized to the negative direction the response's slope will be positive, whereas after being polarized to the positive direction the slope will be negative.

The above-calculated $R(H)$ curves give good agreements with the experimental results for the sample of Co(50A)/NiFe(5A)/Cu(30A)/Co(5A)/NiFe(50A) shown in Fig. 8. The voltage output of that sample was measured at room temperature using the four-point probe method with application of 10 kHz, 30 Oe and 10 kHz, 15 Oe ac magnetic fields, respectively. The angle of the field with the sense current and the easy axis of the sample is 45°, the same as simulated above.

Moreover, many details can be shown from the simulation results. For example, in the simulation of the minor loop (Fig. 7(b) or (c)), the soft component is switched but the magnetization in the hard component should rotate along a Rayleigh loop [14]. Simulations without the Rayleigh loop for the hard component could not give rise to the distortion phenomenon as shown in Fig. 8(b) and (c). The existance of a Rayleigh loop in the hard component will be harmful to our memory design. It will result in gradual degrading of output and finally destruction of the remanent state in the hard component after enormous numbers of readout switching. We will discuss this problem thoroughly elsewhere [15].

IV. Realization

We have fabricated a 1-b GMR memory cell with a storage/sense line and a word line onto the neoceramic substrate, as illustrated in Fig. 9. A brief outline of the fabrication method is given in the following. The materials of the storage/sense line are as given: Co(50A)/NiFe(5A)/Cu(30A)/Co(5A)/NiFe(50A). The thinner NiFe and Co layers were formed to enhance interfacial scattering, which increases the MR ratio to two times as large as that of Co(50A)/Cu(30A)/NiFe(50A), and the sandwich structure is comprised of two ferromagnetic components: the hard component Co(50A)/NiFe(5A) and the soft component Co(5A)/NiFe(50A). To prepare these samples, an RF sputtering system was employed. Uniaxial anisotropy, important both for memory storage and for the way that a bit is selected [1], is induced by a magnetic field of 15.5 Oe applied in the plane of the films during sputtering. The preferred axis is chosen to lie along the longitudinal direction of the sandwich stripe to eliminate the so-called curling distance. Thereafter an ac magnetic field anneal (300°C × 80 Oe × 2 h) was executed, and it was found that the ac thermal treatment works to increase the slope of the $R(H)$ curve. The above sandwiches were patterned into a rectangular shape whose size is 5 μm × 10 μm by optical lithography and ion milling techniques. The storage/sense line was covered with a 0.5 μm thick SiO_2 layer, which served as an insulator, and a Cr/Cu/Cr multilayer was deposited onto the SiO_2 and patterned into the word line. Contact holes were etched in the SiO_2 using the liftoff technique, followed by the structuring of electrodes for the storage/sense line. As regards

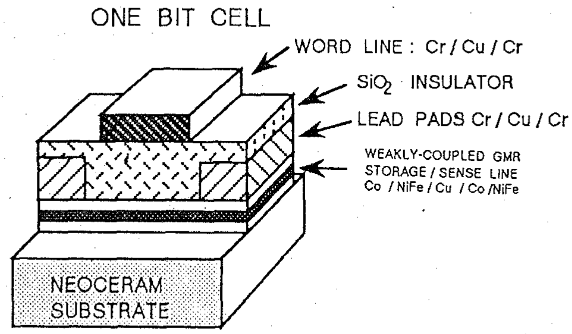


Fig. 9. Experimental apparatus.

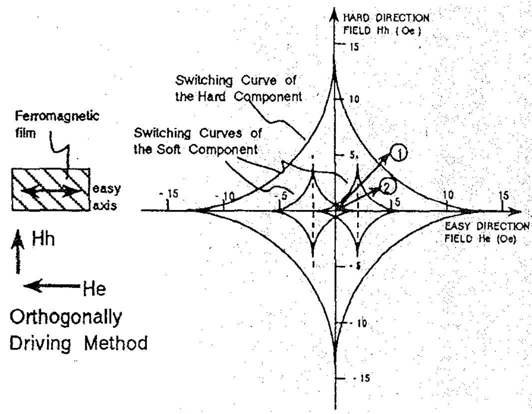


Fig. 10. Switching thresholds.

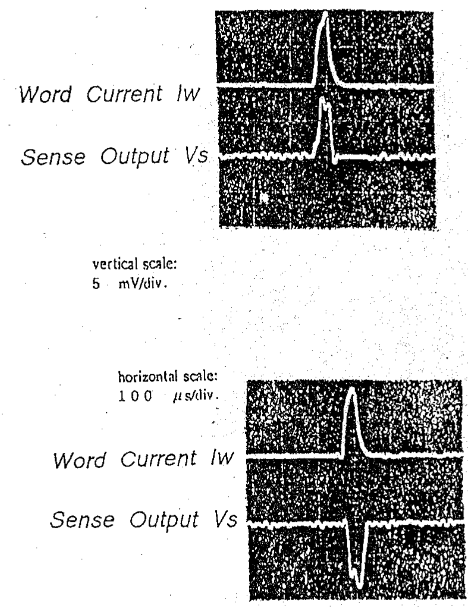


Fig. 11. Pulse sequence of reading process. (a) Readout of 1. (b) Readout of 0.

the Cr/Cu/Cr structure, the usage of Cr(500A) is to make conductor pads as strong as Cu(9000A)'s mechanical strength is soft. A combination of a sense current flowing along the GMR line and a exciting current flowing along the word line can realize a 2D selective storage/sense function.

We measured the threshold of the switching field for both the hard component and the soft component using the GMR effect as an analysis tool [16]. As shown in Fig. 10, the switching field in the longitudinal direction is lowered when a transversal field is applied. The outer loop is the hard's and the two inner loops are the soft's. Two loops for the soft component exist because the soft's loop can be shifted left or right by the remanent magnetic moment in the hard component through the ferromagnetic (parallel) coupling. It is apparent that when the tip of the total field vector, comprising the easy direction field and the hard direction field, is outside the outer curve, a writing or a rewriting operation can be realized (case 1 in Fig. 10). A 2D nondestructive readout (NDRO) can be achieved by applying a field below threshold B with the word line. When considering the NDRO problem in the threshold curve of Fig. 10, the vector should be limited to inside the outer curve but outside the inner curves (case 2 in Fig. 10). Limiting the vector outside, at least touching, the inner curves is to switch the soft component thoroughly and thus get a full output. If the tip of the vector is too close to the outer curve, an instability against wall creep [4] will result. Thus the threshold at point A in Fig. 8 will be generally used to monitor the state of the hard component.

We conclude that the NDRO signal level is almost the full response of that GMR element in our design. You can find this to be true by comparing Fig. 8(a) with Fig. 8(b) or (c). This advantage explains the double-humped shape of the $R(H)$ curve.

As mentioned above, the + slope corresponds to stored 1 while the − slope corresponds to stored 0 in minor loops of $R(H)$ responses. Based on this property, data readout is performed by monitoring the response of the sense line against the pulse word current. The magnetic field induced by the word current is set to be smaller than the coercivity of the hard component, but larger than that of the soft component. Therefore, magnetization switching for the soft component occurs with the pulse word current but not for the hard component. When an plus pulse word current Iw passes through the word line, a plus (corresponding to 1) or minus (corresponding to 0) pulse sense output Vs should appears across that GMR storage/sense line. This was proven to be true by the pulse sequence of Fig. 11. This figure shows the response of the storage/sense line against the plus pulse word current of 25 mA for the fabricated element. The output voltage of the storage/sense line increases for the 1 state shown in Fig. 11(a) and decreases for the 0 state shown in Fig. 11(b) since the resistance of the GMR sandwich is high for the antiparallel spin configuration and low for the parallel spin configuration. The sense current applied into the storage/sense line is 5 mA, and a sense output voltage of 8 mV appears. The read/write energy can be quite low. Furthermore, the tests indicated that a stable readout state involving 3×10^8 excitations can be achieved. Thus this element is confirmed to have an NDRO property.

V. Conclusions

In the weakly coupled sandwiches Co(50A)/NiFe(5A)/Cu(30A)/Co(5A)/NiFe(50A), we found a storage mechanism: The slope of the minor loop of the resistance versus the field curve $R(H)$ depends on its magnetization history. That is to say, after being polarized to the negative direction the response's slope will be positive, whereas after being polarized to the positive direction the slope will be negative. Based on the above mechanism, we develop a memory which uses a weakly coupled sandwich for both storing and reading data.

It was demonstrated theoretically and experimentally that weakly coupled GMR sandwiches can be operated in a mode of 2D selection memory and a mode of 2D selection NDRO sense in which only the soft component is switched by the appropriate combination of the easy direction field and the hard direction field.

Compared with other GMR memory designs, our scheme has the following advantages.

1) The cell width is a key parameter for storage density. In the type using antiparallel coupled sandwiches, the magnetizations in the two ferromagnetic layers lie head-to-tail across the stripe, and stored data 1 or 0 is represented by clockwise or counterclockwise magnetizations around the stripe. However, the magnetizations at the edges of the stripe are constrained to lie along the edges due to strong demagnetizing effects in that short transverse direction, and the magnetization gradually curls in the direction of the stored data away from the edge. For this reason the ultimate density limit of this type is limited by the so-called curling distance from the cell edges. In our design, we can induce the easy axis in the longitudinal direction and lie the stored magnetizations along the edge without demagnetizing the field because only a very weak ferromagnetic (parallel) coupling field acts between layers. Therefore the influence of the curling distance will be eliminated thoroughly.

2) In order to get an NDRO, the general method limits the amplitude of the excitating field to a reversible range. But this always results in lowering the readout amplitude. In our scheme the NDRO signal level is almost the full response of the GMR element.

3) Unlike other magnetic memory designs using soft film for storage, our element has a strong antidisturbance capability. The disturbance from a magnetic field with amplitude under the switching threshold of the hard component for storage purposes does not destruct the remanent state.

4) For any uniaxial anisotropic ferromagnetic film, there are two stable states; the magnetization will tend to point in one of two easy directions, and these directions can be used to represent binary data. The fact that the magnetizations in two ferromagnetic layers act independently in weakly coupled sandwiches makes it possible to realize a quarternary storage. The different coercivities between the two ferromagnetic layers can be employed to write states in the two layers, respectively. This research is now in progress in our laboratory.

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